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Optimisation of Thermal Energy Storage Integration in a Residential Heating System

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Abstract

Domestic heating which is dominated by fossil fuels has a large share in the UK total energy consumption. Heat pumps (HP) with thermal energy storage (TES) in combination with renewable electricity generation are a viable low carbon heating option. TES allows the shifting of heating demand to off peak periods or periods with surplus renewable electricity. However, the performance of this scenario must be critically assessed to ensure improvement relative to conventional heating systems. This study presents the design and operational optimisation of a domestic heating system consisting of an Air Source HP coupled with TES. The optimisation is performed on a synthetic heat demand model which requires only the annual heating demand, temperature and occupancy profiles. The results show that the equipment and operational costs of a HP system are significantly higher than for a conventional system. However, the integration of TES and time-of-use tariffs reduce the operational costs of the HP systems and in combination with the Renewable Heating Incentive make the HP systems cost competitive with conventional systems. It is anticipated that the demand model and optimisation procedure enable the design of low carbon heating systems which integrate the heating system with the variable renewable electricity supply.

Keywords thermal energy storage; heat pump; heat demand; optimisation; genetic algorithm.

1 Introduction

Almost half of the UK final energy consumption is for heating purposes and this proportion is even higher in Scotland [1]. Domestic space and water heating demand is responsible for the majority of this end use and is expected to fall only slightly due to the low construction rates. The provision of domestic heating in the UK is dominated by fossil fuels, with gas as the most common fuel. Therefore, there is a large potential and need to reduce the environmental impact of domestic heating by decarbonising the heating systems. One option of heating system decarbonisation is the utilisation of heat pumps to fulfil the heating demand. The main premise of this effort is to use electricity generated by renewable sources to provide space and water heating. It should be noted that the decarbonisation effect will not materialise as long as the power generation side relies heavily on fossil fuels. The integration of the heating and electricity networks also expands the opportunities for demand side management. One of these opportunities is the combination of heat pumps with thermal energy storage (TES) to shift electrical load from on-peak to off-peak hours [2], and in the future to times with surplus renewable electricity.

The implementation of heat pumps, with or without TES, in residential heating systems has been widely studied in the literature. Tassou et al. explore the early implementation of heat pumps in the UK and compare its economic performance with typical heating systems in the late 1980s [3]. Technological improvements and supporting policies have promoted heat pumps beyond the early stage limitations. A recent review on domestic heat pumps is given by Staffell et al. [4]. Results from a field trial in the UK are also available to illustrate the real performance of the technology [5]. The effects of off-peak tariff periods and building fabric characteristics on heat pump annual performance are investigated by Cabrol and Rowley [6]. The effects of collective heat pump load shifting in UK dwellings are illustrated in the work of Kelly et al. [7]. In a higher spatial level, Hedegaard and Balyk develop a linear programming model to optimise the integration of heat pumps and storages in the future Danish energy system [8]. While heat pump-TES systems have been widely studied, a systematic optimisation study which takes nonlinear effects, e.g. heat pump coefficient of performance, into account is required to design low carbon heating systems that are competitive with conventional heating systems.

TES systems have been studied to a great extent and several textbooks on this topic are available [9-11]. In general, TES can be categorised into three types depending on the main energy storage

mechanism, namely sensible, latent and thermochemical energy storage. Sensible storage in a form of hot water storage is the most widely implemented TES in residential heating system. It is estimated that the maximum combined storage capacity of hot water storage in the UK houses is around 80 GWh [12]. Latent TES utilises the phase change enthalpy of a material to store thermal energy and has higher energy storage density compared to sensible TES. This characteristic is particularly advantageous in a space-limited application, such as residential dwellings. Thermochemical energy storage has an even higher storage density, but currently it is the least mature type of TES. The higher system complexity of thermochemical energy storage also implies that the additional benefits need to be assured before integrating it in a specific application [11].

Design and operational optimisation are important to ensure improvements, both financially and environmentally, in the installation of new energy systems. This is particularly relevant when the electrical and thermal grids are intertwined in the future smart energy system [13]. The implementation of heat pumps can be seen as an early step towards this integration. Heat pump-TES systems also have the capability to increase the flexibility of heating systems, for example by operating the heat pumps with cheaper electricity during off-peak hours. Such flexibility needs to be assessed appropriately before system installation in order to avoid unwanted effects, for instance undersized heat pump capacity which might worsen the overall economic performance by increased utilisation of electric resistive heating to cover the heating demand.

This work presents an optimisation study of a residential heating system which main equipment includes heat pump and thermal energy storage. The main objective is to investigate the economic performance of different heat pump and TES arrangements in terms of their annual operational and total cost. Both standard and Time-Of-Use electricity tariffs in the UK are considered in the cost calculation. Furthermore, the influence of a recently introduced Renewable Heat Incentive (RHI) scheme on the results is also presented. One of important inputs to an energy system optimisation model is energy demand data. The availability of such data for UK residential dwellings is relatively sparse due to the lack of energy monitoring projects. A generic heat demand model is developed in this study to produce a heating demand profile which serves as an input to the optimisation model.

2 Model description

A design and operational optimisation model typically contains equipment models and requires several types of input to produce the intended outputs. In this study, the heating system model is comprised of a heat pump and a hot water tank. The heat demand profile, technical equipment data and relevant financial data are the model inputs. The main output of the model is the annual operational cost of the heating system.

2.1 Heat demand model

A real measurement-based demand profile with complete supporting information is hard to obtain and rarely available in the literature. For example, hourly gas and electricity consumption for several houses in the Milton Keynes Energy Park project are available, but details on housing characteristics and social information are missing [14]. Thus, this study employs a heat demand model to generate synthetic heat demand profiles.

In reality, heating demand depends on numerous factors, such as weather conditions, building characteristics, occupancy profile, installed heating system and occupant's behaviour. A heat demand model typically reduces this complexity by various simplifications depending on the modelling approach. Residential energy demand can be modelled by two modelling approaches: top-down and bottom-up [15]. The top-down approaches rely on highly aggregated historical energy consumption data and are relatively straightforward to develop. On the other hand, the bottom-up approaches, which can be further categorised into bottom-up statistical and bottom-up engineering approach, require more detailed input information (e.g. building characteristics and billing data) and can be computationally intensive. Typical approach in developing bottom-up models is by using a building performance simulation package, e.g. EnergyPlus [16] and ESP-r [17].

In this study, a synthetic heat demand model is developed by combining different aspects of the aforementioned modelling approaches: aggregated consumption data from the top-down approach and occupancy data from the bottom-up approach. The model requires the total annual heating demand, external temperature data and occupancy profile as inputs. The latter two inputs are selected over other influencing factors, e.g. solar gain, due to their relative importance as reported by various studies [18-20]. It has been shown for the low-voltage electricity network that the inclusion of the user occupancy and activity profile in the load model leads to more realistic load profiles [21]. The model is based on the energy signature method, where the heating demand is assumed to be a linear function of external temperature [22, 23]. The working status of the heating system is dependent on external temperature and occupancy profile (Eq. 1). Heating threshold temperatures T_{th} are defined as the ones below which heating systems starts working and divided into active T_{th}^{ac} and inactive threshold temperature T_{th}^{in} . These two temperature levels correspond to the activity status of the occupants, with sleeping counts as an inactive period. Occupancy profile of 2 adults working full-time is assumed in the calculation. This corresponds to a scenario which has an unoccupied period from 09.00 to 18.00 during weekdays [24]. The signature variables k_1 and k_2 are computed to match the annual demand with the heating hours, as formulated in [23].

$$\dot{q}(t) = \begin{cases} k_1^{ac} \cdot T_{ext}(t) + k_2^{ac} & \text{if } T_{ext} < T_{th}^{ac} \text{ and occupants are active} \\ k_1^{in} \cdot T_{ext}(t) + k_2^{in} & \text{if } T_{ext} < T_{th}^{in} \text{ and occupants are inactive} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Domestic hot water (DHW) demand is included by calculating the draw profile with DHWcalc software [25]. In estimating the DHW draw profile, DHWcalc requires a number of inputs, such as house type, mean daily draw-off volume and probability distributions of the draws. Table 1 shows the distribution used in this study. The 10% daily draw assumption during the unoccupied hours (09.00-18.00) is chosen to consider the small irregularity in occupancy profiles and possible demand from appliances.

Table 1: *DHW probability distribution*

<i>Time period</i>	<i>Ratio of daily DHW-volume</i>
07.00 – 09.00	50 %
09.00 – 18.00	10 %
18.00 – 23.00	30 %
23.00 – 07.00	10 %

Figure 1 illustrates an example of synthetic heat demand profile generated by the model. The annual energy consumption of the modelled dwelling is assumed to be the average energy for space and water heating in a Scottish dwelling, i.e. approximately 15000 kWh/year [26]. The general shape of the synthetic heat demand profile is comparable to houses with similar annual consumption in Milton Keynes Energy Park [14].

2.2 Heat pump model

The performance of a heat pump can be quantified by the coefficient of performance (COP), which is defined as the ratio between the useful thermal power and the input electrical power. The real value of COP is affected by different variables, such as external temperature, supply water temperature, inlet water temperature and load factor. Simplifications can be taken in order to reduce this complexity, but this should be done with care as it can affect the optimal control result. For example, it has been shown that a simplified model which neglects the dependency of the COP on the external temperature can produce higher electricity consumption, relative to the more complex model, in the optimisation results [27].

The heat pump in this study is modelled by empirical approximation with the COP as a function of temperature lift. The temperature lift is the difference between the supply water temperature, which is taken as a constant at 50°C, and the external air temperature. Required data to produce the fits are derived from manufacturer's data [28]. Heat pump capacities are also selected from available model in

the market, in this case 5, 8.5, 11.2, and 14 kW.

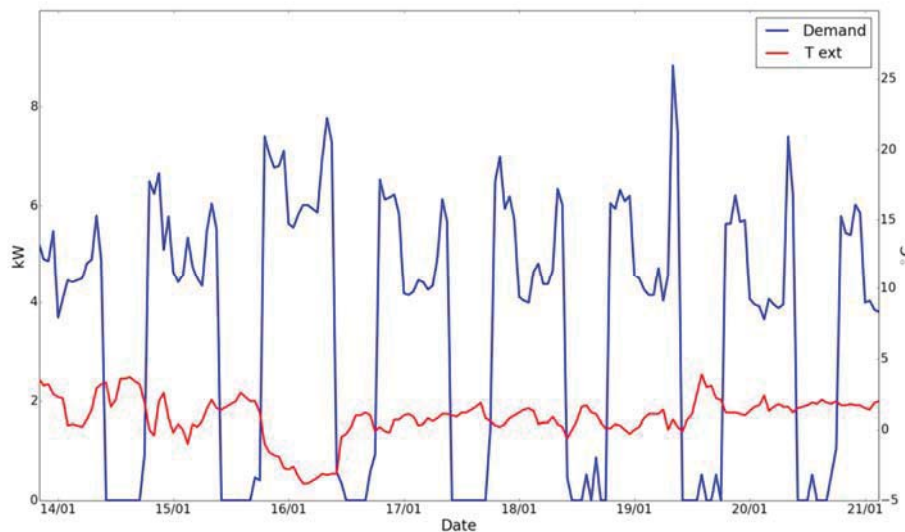


Figure 1: *Example of synthetic heat demand profile*

2.3 Thermal energy storage model

Thermal energy storage included in this study is a typical domestic water tank with volume range 120 - 300 L. Maximum energy charge/discharge rate and standby loss are included in the model (Table 2), while thermal stratification effects are neglected in the current study. The TES operation is constrained in such a way that it can only be charged or discharge in a time-step. Furthermore, charging is limited to occur during off-peak electricity period.

Table 2: *TES standing loss and charge/discharge rate*

TES Volume (L)	120	150	180	210	250	300
Standing loss (kWh/day)	1	1.38	1.63	1.9	2.21	2.43
Max. charge rate (1/h)	0.25					
Max. discharge rate (1/h)	0.14					

2.4 Optimisation framework

The optimisation framework consists of the heat demand model, capacity and operational optimisation, as illustrated in Figure 2. The annual demand profile from heat demand modelling serves as an input to the capacity optimisation. The resulting component capacities are passed into the operational optimisation routine. In this step, typical days are selected to significantly reduce the time steps and consequently, computational time. The typical days are chosen based on empirical examination of the annual demand profile, with one representative day for each season. Both capacity and operational optimisation utilise the NSGA-II genetic algorithm [29].

The capacity optimisation step selects the heat pump size and TES capacity pair which can cover the whole annual demand with minimum energy overcapacity and capital costs. Information on equipment costs are gathered from manufacturer's datasheet. It should be noted that the typically installed backup resistance heating is not included in the present calculation.

The operational optimisation is performed separately from the capacity selection to reduce the complexity. This means that for a given heat pump and TES capacity pair, the operational optimisation step produces the optimum heat pump load factor configuration for each typical day. The selected simulation time step in the operational optimisation is one hour. The objective function is to minimise energy cost, which is calculated by multiplying the electricity consumption by the corresponding tariff.

The annual operational cost is calculated by multiplying the optimisation result for the typical days to the number of days in the respective seasons.

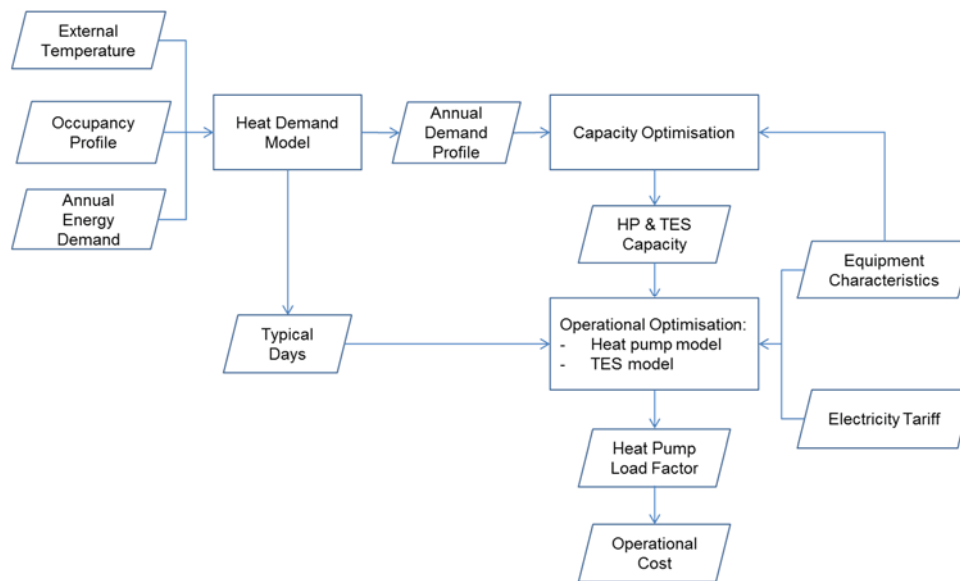


Figure 2: *Optimisation framework*

Three types of electricity tariff are considered: Standard, Economy 7, and Economy 10. Both Economy 7 and Economy 10 are two rates tariff structure with off-peak duration of 7 and 10 hours, respectively. It is assumed that the off peak hours for Economy 7 are from 00.00 to 07.00, while Economy 10 off peak hours are between 00.00 – 05.00, 13.00 – 16.00, and 20.00 – 22.00. The Standard tariff is used for the Heat Pump only scenario, while the other two are used for the Heat Pump-TES scenario. Table 3 shows the summary of the electricity tariffs [30].

Table 3: *Electricity tariffs*

Tariff	On-peak (£/kWh)	Off-peak (£/kWh)
Standard		0.144
Economy 7	0.1747	0.065
Economy 10	0.1744	0.071

3 Results and discussion

The capacity optimisation step found that the optimum heat pump size for the given case is 8.5 kW, while all storage size can be employed, with rising capital cost as the volume increases. This heat pump capacity is the same magnitude as the maximum winter heating demand; see Figure 1 for a representative week in January. The maximum winter heating demand could not be met with the smaller capacity heat pump even with support from the largest TES tank. This is due to the maximum charge/discharge rates of the TES tank (Table 2). For example, the 300 L tank has a storage capacity of around 14 kWh at a temperature difference of 40°C which gives a maximum discharge of 1.96 kW. Thus the heat pump with 5 kW capacity plus the largest storage tank can only meet a maximum demand of 6.96 kW which is well below the maximum winter heating demand. Therefore, the larger capacity heat pumps could supply the maximum charging capacity to the TES even at the maximum winter demand and are thus clearly oversized.

Figure 3 illustrates the result of operational optimisation for the 8.5 kW heat pump and 180 L TES heating system on the Time-Of-Use tariffs in a typical winter day. It can be seen that the heat pump produces more than the demand during off-peak hours due to TES charging. The TES starts contributing to cover part of the demand by discharging during on-peak time. The TES discharge power increases as ambient temperature drops in the evening because the optimisation routine tries to minimise electricity consumption (i.e. utilise the heat pump during higher COP conditions). In this particular

winter day, the TES manages to shift approximately 13% of on-peak demand to off-peak time. Total load shifting requires significantly larger storage capacity, e.g. 1000 L storage as reported in [7]. However, space limitations in typical UK dwellings call for a higher density TES, such as latent storage, if the aim is total load shifting.

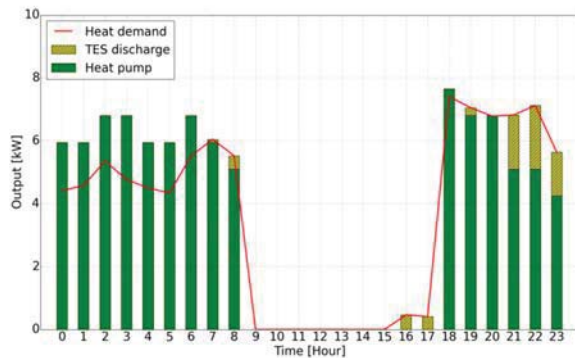


Figure 3(a): Winter day, Economy 7

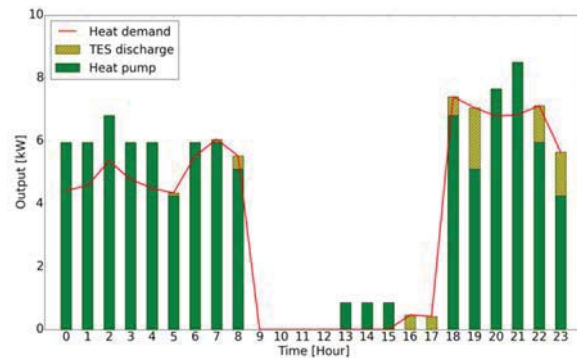


Figure 3(b): Winter day, Economy 10

Table 4 summarises the annual operational cost of an 8.5 kW heat pump with different storage volumes compared with the heat pump only and conventional condensing boiler scenario. As expected, the operational cost of the heat pump-only scenario is higher than those with TES. Furthermore, it is clear in both time-based tariff structures that the annual operational cost is decreasing as storage capacity increases. This even leads to a competitive running cost between the scenario with 300 L storage and a conventional boiler. Overall, the operational cost of a new condensing boiler is lower than that of heat pump due to the relatively low price natural gas. Furthermore, there are small differences between resulting operational costs with the two Time-Of-Use tariffs. This can be attributed to the imposed constraints on charging/discharging time. Since there are two hours of off-peak time during typical on-peak usage time in the Economy 10 tariff, relaxing the aforementioned constraints may improve the operational cost.

The total cost of all heating system options is calculated with the assumption of 20 years equipment lifetime and 3% interest rate. The results are illustrated in Figure 4. All heat pump scenarios have a significantly higher total cost than boiler scenario. Again this can be attributed to the relatively higher price of electricity compared to natural gas and the significantly higher equipment costs for the heat pump with TES system. For scenarios with TES, a higher storage volume produces lower total cost, albeit relatively small. However, total cost is lower for heat pump with TES than heat pump only. This is because the operational cost savings from TES compensate for the capital cost of the storage.

Table 4: Annual operational cost (£)

TES Volume (L)	120	150	180	210	250	300
Economy 7	724	710	700	694	681	654
Economy 10	723	717	695	697	675	652
Heat Pump only				889		
Boiler				654		

Recently, the UK government launched the domestic Renewable Heating Incentive (RHI) policy in order to foster the implementation of non-fossil fuel domestic heating systems [31]. It is a financial incentive policy which offers payments to the consumers for the amount of heat their system produces for seven years. Eligible heating systems are biomass boilers, heat pump (both air and ground source), and solar thermal. The current tariff for air source heat pump is £ 0.073/kWh. The inclusion of RHI in the calculation of total cost has significant impact, as shown in Figure 4. It is clear that RHI reduces the operational cost by a large margin, and makes the heat pump scenarios cheaper than the gas boiler

option.

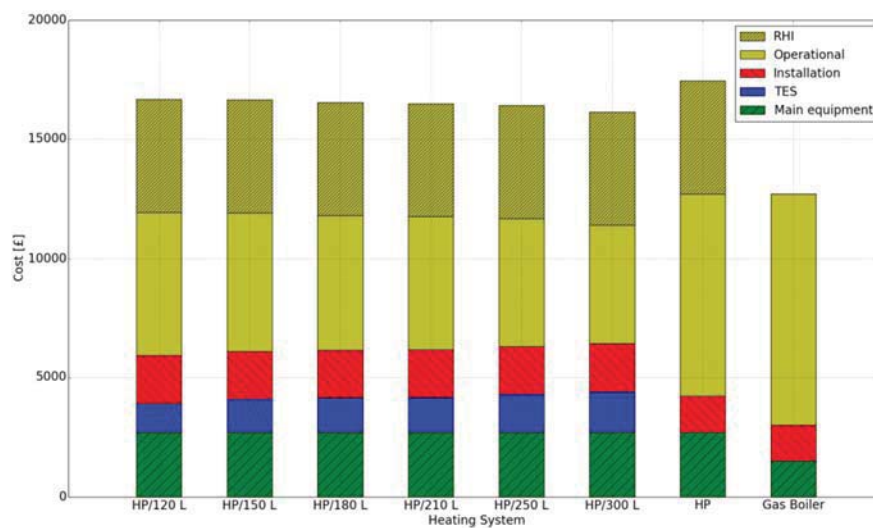


Figure 4: Total cost of different heating systems

3.1 Study limitations and future works

As in any modelling-based study, the results of this study have to be considered along with the model assumptions and limitations. Briefly described below are examples of these limitations in the present study.

The heat pump model assumes a constant supply water temperature. A heat pump model with dynamic supply water temperature can increase the COP, as shown in [32]. The decision to exclude this in the present study is to reduce the model order by not having a detailed building thermal model. This is because the overall study is aiming for design and operational optimisation of heating systems on multiple dwellings/district level. The detailed building thermal model would increase the computational complexity and cost significantly for district level optimisations and thus make comprehensive optimisations intractable. On the other hand, the synthetic heat demand model can be integrated with user occupancy and activity profiles generated from Time Use Surveys [21] to generate district level heat demand profiles which retain the stochastic variations inherent in these systems.

In the current TES model, stratification effects are not accounted for. These factors may have non-negligible impacts on the performance of the TES model. Furthermore, an electric immersion heater, which is normally installed within the tank, should be included in the next iteration. This might show an interesting trade-off between oversizing the heat pump, TES size and immersion heater operation regime over the operating period. The TES charge/discharge control in the current study is solely based on off- and on-peak time from the corresponding electricity tariff. Other types of control are available and might improve the optimisation results.

The selection of typical days in this study was not performed in a systematic way. Several methods in systematic determination of typical days have been proposed in the literature [33, 34]. It is interesting to see the effect of implementing such methods in the optimisation results.

4 Conclusions

An optimisation model to study the operational and total cost of a heat pump and TES-based residential heating system has been developed. Included in the optimisation framework is a heat demand model which is capable of producing heat demand profiles based on cumulative heating demand, ambient temperature, and occupancy profile. The design and operational optimisation of a residential heating system were then performed using the output of the heat demand model and manufacturer's equipment data as inputs. Different UK electricity tariffs (2013) were employed in the calculation of the operational

cost of different heating system arrangements.

The results of operational cost calculation illustrate that heat pump-based heating systems, with or without TES, have significantly higher cost than natural gas-based heating system. However, for cases with TES the operational costs are lower than the heat pump-only scenario and decrease as the storage volume increases. For a TES tank of 300 L the operational cost are comparable to the conventional gas boiler system. It was shown that with the currently assumed control scheme, the operational cost for the Economy 7 and Economy 10 tariffs are almost equal. This is likely to change if different occupancy scenarios are considered.

Total costs of the studied heating systems have a similar trend since operational cost has the largest share in the total cost. However, the recently introduced RHI can reduce the operational cost and make heat pumps a more attractive option for end users in the UK.

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